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# Non-Contact laser ultrasound (N-CLUS) system for medical imaging and elastography

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***Abstract***— MIT Lincoln Laboratory, the Medical Device Realization Center (MEDRC) at MIT, and the Massachusetts General Hospital (MGH) are collaboratively developing a novel optical system that acquires ultrasound images within the human body without physical contact to the patient. The system is termed, non-contact laser ultrasound (N-CLUS) and yields anatomical images in tissue and bone and can also measure elastographic properties, in-vivo, all from an operational standoff of a few inches to several meters as desired. N-CLUS employs a pulsed laser that converts optical energy into ultrasonic waves at the skin surface via photoacoustic mechanisms, while, a laser Doppler vibrometer measures reflected-emerging ultrasonic waves from tissue at depth at the skin surface. The key of the N-CLUS approach is driven by shallow optical absorptivity that creates an acoustic source that enables ultrasound propagation deeper into the tissue.

We discuss the motivation of the non-contact laser concept, its development path involving signal generation, skin and eye safe laser measurement, and system design perspectives. Elastogrphic measurements are then demonstrated with determination of bone elastic moduli for beef rib within tissue. N-CLUS images from soft tissue specimens are also compared with commercial ultrasound, showing that the noncontact optical approach may have potential as a viable method in medical ultrasound.

**Keywords—** medical ultrasound imaging, non-contact laser ultrasound, photoacoustics, laser Doppler vibrometry, elastography

## 1. Introduction

Ultrasound (US)[1] is an ideal imaging modality used in medical practice - portable, inexpensive, and no known bio-effects while producing images with excellent resolution. Despite these advantages, MRI and CT are the dominant modalities while, accepting higher cost and some health risks. US is typically taken with hand held transducers that depend on the operator's applied pressure and selection of angle planes with no fixed acquisition frame. This leads to inter-operator variability – significant image distortion with limited feature accuracy/confidence, especially upon repeat measurement and is the primary reason US is unable to compete with MRI and CT.

### *A. Appeal of non-contact laser ultrasound*

N-CLUS has the potential to provide a fixed reference measurement capability in a portable, low cost platform. Excitation and receive locations could be revisited with spatial precision, thus enabling the capability to monitor subtle changes in geometry and mechanical properties over time with much less error than that of hand-held transducer systems. Unlike contact transducers, optical ultrasound does not impart large-scale tissue deformation due to surface loading thus, producing distortion in the ultrasound image. Another appeal of conducting optical ultrasonic measurements comes from the need to avoid contact with damaged or burned skin, traumatized regions, tissue with risk to infection and contamination, and areas difficult to access. The advantages of N-CLUS merit investigation and development to yield medical imaging systems that could compete with MRI and CT. Such systems would enable numerous new US applications.

N-CLUS is achieved via short optical pulses that generate ultrasonic waves in the body. Short pulses of optical energy are converted into mechanical energy via thermal expansion causing the optically absorbing material to rapidly deform, thus launching a propagating mechanical wave response[6]. The emerging wave returning from the body interior is then measured at the skin surface with a laser Doppler vibrometer. Research on non-contact acoustic and vibrational ultrasound has been ongoing for the past decade[7-12]. Much of the focus has been in the field of photoacoustic tomography (PAT) that is becoming increasingly popular in studies to image near-surface shallow capillaries in animal tissue. The PAT technique employs an optical source to induce the PA effect where contact transducers are used to record the direct, up-traveling acoustic response. In PAT, optical penetration in bio-tissue can range from sub-millimeter to a centimeter and exploits spatial variations in optical absorptivity that map to spatially varying tissue properties[2]. However, optical scatter severely limits the effectiveness of PAT. The approach developed in this paper encompasses N-CLUS that exploits optical wavelengths that are uniformly absorbed at depths significantly less than 1 mm from the patient skin surface. In turn, a laterally consistent acoustic source is created generating coherent, broadband ultrasonic waves capable of propagation well into the far field and back.

Recent studies explore the addition of laser Doppler vibrometry as a sensing device in place of contact transducers making the PAT system totally optical and non-contact[11,13]. However, for optical measurement systems to compete with practiced medical ultrasound, propagation depths of several inches are needed to probe the body while, maintaining sub-millimeter resolution, excellent SNR, and reasonable acquisition speed.

In this paper, we discuss the key mechanisms and demonstrate fully non-contact laser ultrasound for anatomical imaging in soft tissue and elastographic property estimation in bone related to bone strength, health, and injury. We also present the potential of such a system to form images in animal tissue and a human test subject.

### *A. N-CLUS Wave Generation with Laser Measurement*

Figure 1 shows PA excitation is used in conjunction with a laser Doppler vibrometer (LDV) to acquire ultrasonic waves without patient contact. PA phenomena develop from optical energy, in the form of very short laser pulses (picoseconds to nanoseconds), that interacts with a highly optically absorptive target surface, such as water or biological tissue where optical energy rapidly converts into heat[6,17]. This instantaneous heating creates a concentration of mechanical stress within the irradiated tissue patch. Because the tissue is no longer in mechanical equilibrium, the stress must dissipate and generates a propagating acoustic wave into the tissue mass.

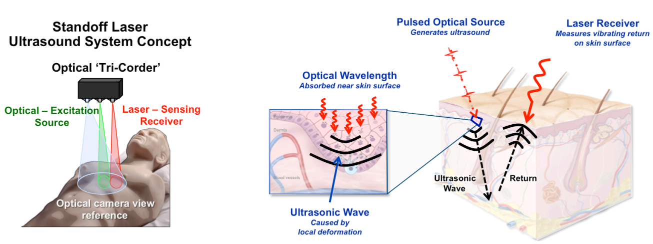


**Fig 1**. Notional non-contact LUS (N-CLUS) [14-17] system to acquire elastic wave images and material properties of the body interior without contact with the subject. Pulsed light is absorbed over a very short distance within the skin surface layers creating ultrasonic waves. The ultrasonic returns reflected off internal structural boundaries are measured with a LDV[18].

## II. STANDOFF – N-C LUS MEASUREMENT SYSTEM

A demonstration system was developed to 1) explore phenomenology controlling skin and eye safe optical absorption that generate useful ultrasonic waves, 2) explore the variety of elastic/ultrasonic waves that are generated from a photoacoustic source to determine elastic moduli in bone, and 3) produce anatomical images of biological tissue interior and compare to standard medical ultrasound.

We use a 1550nm laser that is eye and skin safe to act as a photoacoustic source in tissue. A fast steering mirror positions the laser beam onto the sample surface within sub-millimeter increments in x and y translation. A Polytec RSV-150 LDV receives US returns with an eye and skin safe 1550nm wavelength transmission at 10mW. US time series are collected on a laptop computer driven by LabView software. Typically, scan lines are steered across the sample. A compilation of scan lines can then be used to form a 3D time image that can be processed and converted to depth. A single scan line can be used to form a 2D cross-sectional profile in the tissue specimen.

The bi-static source and receiver separation distance is varied to accommodate standard data processing algorithms to remove the effects of normal move out (NMO)[20] and diffraction of point scatterers[20]. The N-CLUS experimental measurement configuration is shown in Figure 2.

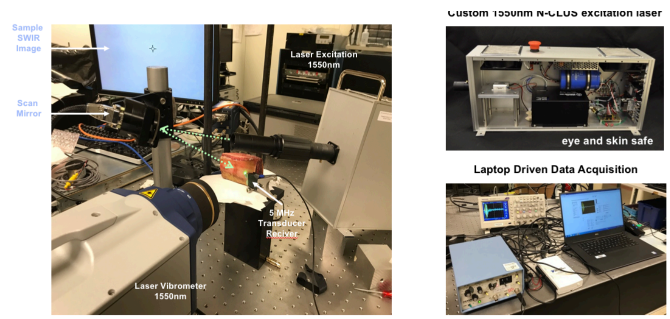


**Fig 2.** Non-contact LUS experimental system using a customized photoacoustic source emitting a 1550nm eye and skin safe pulse for excitation and a commercial LDV. The LDV receive system is a Polytec RSV-150 (1550nm eye and skin safe). A fast steering mirror is used to scan and position the optical beams on the bio-tissue specimens.

### *A. Observed wave types induced by N-CLUS sources.*

We observe that a narrow optical beam, 3mm in diameter, can photoacoustically generate the full suite of elastic/ultrasonic waves that are well described in the literature[19,20]. In biological tissue, both compressional and shear waves are generated.

The elastic wave propagation in shallow bone in a beef steak sample is shown in 2D time sonograms in Figure 3. Compressional (body and surface) and shear (body and surface are present for direct and reflected transmissions. Direct wave transmissions are surface waves and are depicted by linear sloping events that 'fall' away from the near trace. The steeper the slope, the slower the wave velocity is. Table 1 shows the elastic moduli[24] computed from the measured elastic wave speeds in the beef bone.

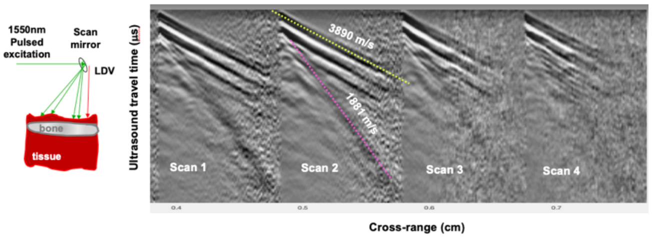


**Fig 3.** Elastic moduli determined from N-CLUS measurements of shallow bone in beef steak sample. The measurement utilizes a far-offset bi-static photoacoustic source and LDV receiver geometry inducing US waves traveling along the bone surface. Compressional (Vp) and Shear (Vs) are measured simultaneously from the given arrangement. The maximum source to receiver offset is approximately 3-4 inches apart while, source location spacing is 1 mm.

| Young's Modulus | Poisson's Ratio | Bulk Modulus | Shear Modulus |
|---|---|---|---|
| $\rho V_s^2 (3V_p^2\ 2V_s^2) / (V_p^2 - V_s^2) /3)$ | $(V_p^2 - 2V_s^2) / 2 (V_p^2 - V_s^2)$ | $\rho (V_p^2 - 4V_s^2/3)$ | $\rho V_s^2$ |
| 21.0 GPa | 0.3474 | 22.5 GPa | 7.6 GPa |

**Table 1.** Elastic moduli of shallow bone in beef steak sample determined from N-CLUS measurements. Independent laboratory stress-strain measurements yield the above moduli and are within a few percent. Elastic moduli expressions are derived in Ref 24.

### *B. N-CLUS patient eye and skin safe performance*

Critical factors to consider when designing an operational system for use by physicians are 1) patient safety and risk related to system hazards, 2) image quality, 3) effective coverage, 4) size, weight, power, and 5) cost. We next examine the effects of the optical excitation wavelength on SNR, image quality, while maintaining skin and eye safety. Image quality is examined for four different optical excitation wavelengths that span the near to short wave infrared, 810nm, 1064nm, 1550nm, and 2000nm. For each of these wavelengths, a 7 ns pulse is transmitted where the fluence level is held constant at 21 mJ/cm$^2$ with a laser spot size of 2 mm on the sample surface, using an variable wavelength laser. A beef sample is used for the measurements that contains two 1mm-diameter rods that are inserted lengthwise into the sample. The optical beam is scanned across the sample in an off-end shoot pattern while the 2D cross-section of time series are recorded.

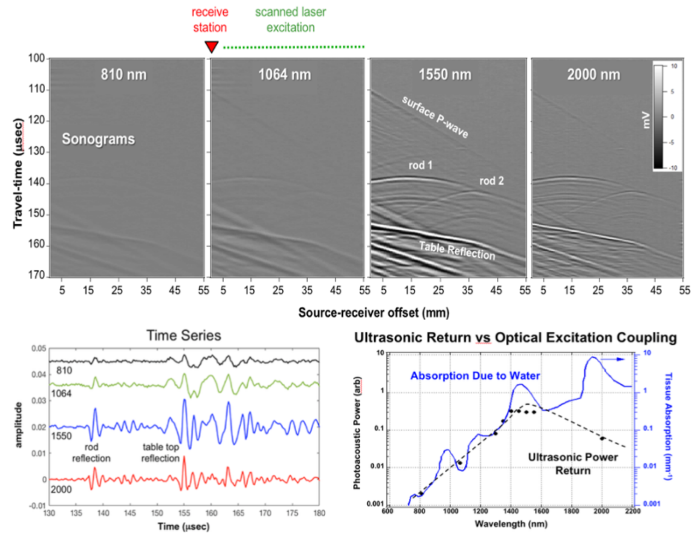


**Fig 4.** Top: N-CLUS sonograms for four wavelengths with a constant fluence. Images are normalized to the maximum amplitude among the four sonograms. Bottom left: Comparison of measured ultrasonic time-series traces for measurements directly over a 1 mm rod at four optical wavelengths. Bottom right: summed ultrasonic power of measured ultrasound returns as a function of optical excitation wavelength. Also shown is the optical absorption caused by water (dominant material in bio-tissue) as a function of optical wavelength.

| Wavelength (nm) | Skin safety threshold (mJ/cm$^2$) | Eye safety threshold (mJ/cm$^2$) |
|---|---|---|
| 810 | 33 | $8.3 \times 10^{-4}$ |
| 1064 | 105 | $5.0 \times 10^{-3}$ |
| 1550 | 1000 | 1000 |
| 2000 | 100 | 100 |

**Table 2:** ANSI Z136.1-2007 skin and eye safety optical exposure levels. Optical fluence levels are held at 21 mJ/cm$^2$ while, maintaining a laser spot size of 2mm on the sample surface. All wavelengths are compared to skin and eye safety limits[21].

The sonograms show ultrasonic reflection events sharpening with increasing optical wavelength excitation. The ultrasound amplitudes increase with increasing optical wavelength up to 1550 nm, then show a relative decrease for the 2000 nm case. Although the ultrasonic frequency content generated by the 2000 nm source is high and the associated image exhibits the best temporal resolution, the signal amplitude drops. This drop is likely caused by increased ultrasound wave attenuation acting more severely on higher frequency components as the ultrasound wave travels through the beef sample.

The 1550 nm and 2000 nm sources produce the best SNR images that show the features of the metal rods, steak, and table top interface while optical excitation is within skin and eye safety limits. The 810 nm and 1064 nm produce weaker SNR images for optical excitation fluence levels above the eye safety threshold. The high optical absorptivity of the 1550 nm wavelength provides the highest threshold, which allows much higher optical powers to improve SNR while still maintaining safety and offers common commercially ready components.

*C. N-CLUS Imaging in tissue*

N-CLUS ultrasonic images are compared with contact a GE 9 MHz medical ultrasound probe. In Figure 5, US images of a three-inch thick pork sample are shown for the two systems. For N-CLUS, the emitted optical beams are within skin and eye safe levels. The laser vibrometer has a bandwidth of 1 MHz with a 200 microsecond listen time.

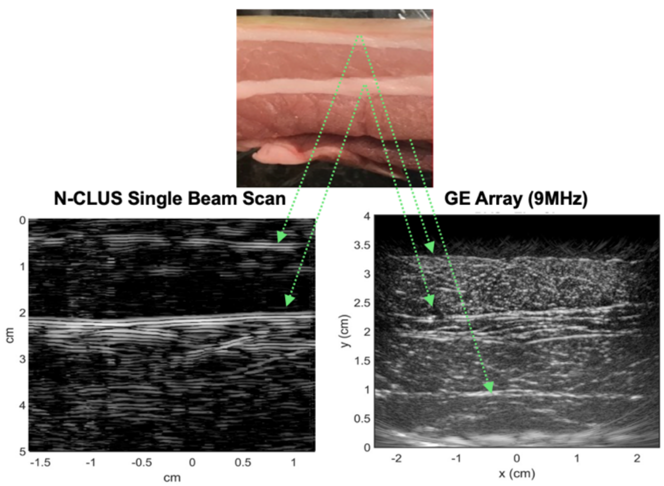


**Fig 5.** N-CLUS sonogram image converted to depth for pork sample. Comparisons are shown for the total N-CLUS (co-located scanned photoacoustic source and scanned LDV beam) (left) and the GE 9 MHz medical ultrasound system (right).

In the N-CLUS and GE images, fat and tissue layer geometries are clearly evident. However, the spatial resolution is significantly better for the, GE 9 MHz system image. The lower resolution quality of the N-CLUS image is primarily due to the higher source bandwidth of the GE system. The GE system is also able to use beamforming methods to further improve SNR.

*D. N-CLUS path forward : stand-mounted, multipixel array*

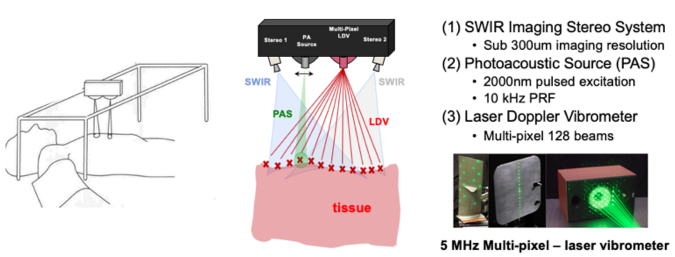


**Fig 6.** Proposed simple stand mount for static N-CLUS acquisition. The optical head is fixed in the stand and can be positioned. Optical excitation and measurement laser beams can be scanned over a body region using fast scanning mirrors. The electronics associated with the optical head can be rack mounted. The system would be portable enough where it could be assembled and used in a clinical setting or remote field forward station.

Commercially available Q-switch microlasers and multipixel laser vibrometers are coming onto the market that can be readily adapted for use in a stand-mounted system within a near term time frame. This system is currently in development at MIT Lincoln Laboratory. In the longer term, there is a significant desire to develop a small portable handheld non-contact optoacoustic system. Such a system will require miniaturization of components and will also require methods to compensate for operator motion and look angles similar in concept to conventional handheld contact ultrasound systems. The use of chip-scale lidar technology is proposed to enable miniaturization and motion compensation capabilities. Moreover, larger numbers of pixels are being proposed to meet operational coverage rates required for full body scan ultrasound.

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